Relationship between surface reflectance in the visible and mid-IR used in MODIS aerosol algorithm - theory

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[1] Data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument that flies in polar orbit on the Terra and Aqua satellites, are used to derive the aerosol optical thickness and properties over land and ocean. The relationships between visible reflectance (at blue, ρ_{blue}, and red, ρ_{red}), and mid-infrared (at 2.1 μm, $\rho_{2.1}$) are used in the MODIS aerosol retrieval algorithm to derive global distribution of aerosols over land. These relations have been established from a series of measurements indicating that $\rho_{blue} \sim 0.5\ \rho_{red} \sim 0.25\ \rho_{2.1}$. Here we use a model to describe the transfer of radiation through a vegetation canopy composed of randomly oriented leaves to assess the theoretical foundations for these relationships. Calculations for a wide range of leaf area indices and vegetation fractions show that ρ_{blue} is consistently about 1/4 of $\rho_{2.1}$ as used by MODIS for the whole range of analyzed cases, except for very dark soils, such as those found in burn scars. For its part, the ratio $\rho_{red}/\rho_{2.1}$ varies from less than the empirically derived value of 1/2 for dense and dark vegetation, to more than 1/2 for bright mixture of soil and vegetation. This is in agreement with measurements over uniform dense vegetation, but not with measurements over mixed dark scenes. In the later case, the discrepancy could be probably mitigated by shadows due to uneven canopy and terrain on a large scale. INDEX TERMS: 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1640 Global Change: Remote sensing. Citation: Kaufman, Y. J., N. Gobron, B. Pinty, J.-L. Widlowski, and M. M. Verstraete, Relationship between surface reflectance in the visible and mid-IR used in MODIS aerosol algorithm - theory, Geophys. Res. Lett., 29(23), 2116, doi:10.1029/2001GL014492, 2002.

1. Introduction

[2] A new generation of space-borne Earth observation instruments has been launched and can be used to monitor aerosols over land [King et al., 1999]. Satellite sensors differ in their measurement capability: MODIS is using a wide spectral range (0.47 to 2.1 μm) to derive the aerosol optical thickness and properties [Kaufman et al., 1997a]. The Multi-angle Imaging SpectroRadiometer (MISR), on Terra, retrieves aerosol properties using a modest spectral range (0.44 to 0.86 μm) but observing the Earth from nine different directions simultaneously along the satellite track [Diner et al., 1989, 1998]. The POLarization and Direction-

ality of the Earth's Reflectances (POLDER) instrument, operating in 1996–1997, using the same spectral range, observed the Earth from a wide range of angles in two dimensions and derived the aerosol properties with the help of polarization [Herman et al., 1997]. The Along Track Scanning Radiometer (ATSR) instrument combines 4 spectral channels (0.55 to 1.65 μm) with two view directions [Veefkind et al., 1998]. In all these instruments the measured signal consists of sunlight reflected by both the Earth surface and the aerosol layer. Some assumptions about the surface reflectance properties and aerosol properties have therefore to be made to separate the aerosol contribution to the signal from that of the surface.

[3] In this paper, we evaluate the MODIS technique that is based on the assumption that the ratios of the surface reflectances in the blue (0.47 μm) and red (0.67 μm) to the reflectance at 2.1 μm are constant in space and time at the fixed values of 0.25 and 0.50, respectively. Our simulations were carried out at 0.44 μm, which has similar characteristics to the MODIS 0.47 μm channel. This ratio was established using remote sensing measurements in the United States [Kaufman et al., l997b] and confirmed in an independent experiment in Israel [Karnieli et al., 2001]. The global application of the technique [Chu et al., 2002] shows that the method works over most terrains for which the surface reflectance at 2.1 μm is smaller than 0.15. However no theoretical basis for this assumption had been developed so far. More specifically, the MODIS technique is based on the fact that sub-micrometer aerosol particles are transparent at 2.1 μm (i.e., smoke and pollution but not dust). The MODIS algorithm first considers the reflectance at 2.1 μm at the top of the atmosphere, and then uses this reflectance value to estimate the surface reflectance in the blue and red channels, using the empirical relationships described above. The aerosol optical thickness and properties are derived directly from the measured excess reflectance in the blue and red channels. In this paper, we provide some theoretical basis in support of the fixed spectral ratio approach, using surface bidirectional reflectance model of Gobron et al. [1997].

2. Model Simulations

[4] We simulate the angular and spectral properties of fully and partially vegetated surface using the plant canopy radiation transfer model developed by Gobron et al. [1997]. This model solves the radiation transfer problem in the case of finite-size oriented leaves uniformly distributed over a scattering soil. The leaves are not clumped into trees, but are distributed in space as illustrated in Figure 1. The model

Figure 1. Artist view of the structurally homogeneous leaf distribution implemented by the canopy radiation transfer model (top), and of the mixed surfaces used in our simulations, here for a fractional vegetation cover of 50% (bottom).

computes the Bidirectional Reflectance Factors (BRFs), ρ_{mixed}, for mixed surfaces (see Figure 1) with fraction f_s of soil and f_v of vegetation ($f_s + f_v = 1$) using a linear mixing between them:

$$\rho_{mixed}(\Omega_o, \Omega) = \Sigma_i f_i \rho_i(\Omega_o, \Omega) \qquad (1)$$

Here, f_i is the relative fraction of the pixel area occupied by surface type i. Allowed surface types include either vegetation with a given leaf area index (LAI) or soils, while Ω_o and Ω denote the solar illumination and satellite observation directions, respectively. The model simulations are limited here to one type of leaf properties and three types of soils. Table 1 summarizes the leaf and soil spectral properties. It is important to note that the optical properties of the leaf and soils used in the present calculations were selected well in advance and independently of the MODIS algorithm and the measurements that serve as the basis for the surface spectral properties in that algorithm. The radiative transfer model has been extensively evaluated and tested against a set of three-dimensional models [*Pinty et al.*, 2001]. The linear assumption used in equation 1 used to represent the angular reflectance of mixed pixels is assumed accurate enough for medium to low spatial resolution sensors. The calculations are performed for a wide range of leaf area index (0.05 to 5), vegetation fraction (0.25 to 1), view zenith angle (0° to 40°) and solar zenith angle (1° to 51°). The relative azimuth between the Sun and the observer is 0°, 90° or 180°.

3. Results

[5] The plant canopy radiation transfer model [*Gobron et al.*, 1997] is used to calculate the spectral reflectance of

mixed scenes using equation 1, where f_v represents the fractional vegetation cover (f_v = 0.25, 0.5, 0.75 and 1.0) and ($1 - f_v$) is the fractional soil cover. The leaf area index (LAI) varies from 0.05 to 5. Throughout the ensemble of simulations, the vegetation density (f_v*LAI) thus varies from 0.01 to 5. Note that shadows due to variability of the height of vegetation and terrain relief are not accounted for in these calculations. We shall evaluate the implications of this issue in the discussion section. Figure 2 shows scatter plots of the simulated mixed surface reflectance at 0.44 μm and 0.67 μm as a function of the reflectance at 2.1 μm for all cases corresponding to medium and bright soils. The vegetation density is represented in color, ranging from dark green for f_v*LAI = 5 to red for f_v*LAI = 0.01. Lines corresponding to the ratios of 1/4 and 1/2, for the blue and red respectively, as assumed in the MODIS algorithm [*Kaufman et al.*, 1997a] are superimposed.

[6] Quasi-linear relationships are observed between the blue (0.44 μm) or red (0.67 μm) and the 2.1 μm channels for a wide range of simulated conditions. The simulated 0.44 to 2.1 μm ratio closely follows the assumed ratio of 1/4 over the whole range of surface reflectance values. In the case of the 0.67 over 2.1 μm ratio, however, the simulated ratios are lower than 1/2 for dark surfaces and larger than 1/2 for bright surfaces. The figure shows a transition from ratios $\rho_{red}/\rho_{2.1}$ around 0.25 for dense dark vegetation (typically forest), to ratios larger than 1/2 for bright soils (see Table 1). In fact, measurements do show that for dense homogeneous forests the relationship between the reflectance in the 0.44, 0.67 and 2.1 μm is such that $\rho_{blue} \sim \rho_{red} \sim 0.25\rho_{2.1}$ [*Remer et al.*, 2001; *Gatebe et al.*, 2001], as predicted by the model. For mixed dark scenes, however the measurements show that $\rho_{blue} \sim 0.5 \ \rho_{red} \sim 0.25 \ \rho_{2.1}$ [*Kaufman et al.*, 1997a, 1997b; *Karnieli et al.*, 2001].

[7] Figure 3 shows similar calculations to those of Figure 2, but this time including simulations with dark soils. The plots are for a limited reflectance range of 0 to 0.2 to emphasize the range that is used by the MODIS analysis. Note also that the color bar indicates the various LAI values instead of the vegetation density (f_v*LAI). As already shown in Table 1, dark soils reduce the reflectance at 2.1 μm much more than in the red or blue wavelengths, thus resulting in a much steeper slope. Such dark soil conditions are typical, for instance, of recent burn scars. Other soil conditions intermediate between dark and medium, would probably end up with a series of different slopes.

[8] It is interesting to see whether the ratios of Figure 2 depend on the view and solar illumination directions. The ratios of the blue and red reflectances to the 2.1 μm

Table 1. Spectral Properties of Leaves and Soils Used in the Simulations

Reflective surface/wavelength	0.44 μm	0.67 μm	2.1 μm
Leaf reflectance	0.054	0.054	0.148
Leaf transmittance	0.005	0.014	0.172
Dark soil reflectance	0.068	0.126	0.140
Medium soil reflectance	0.102	0.238	0.357
Bright soil reflectance	0.139	0.351	0.536

The leaf spectra are based on the leaf model of *Jacquemoud and Baret* [1990] for typical standard conditions of chlorophyll concentration and water content in a healthy leaf. The soil spectra are derived from the database of *Price* [1995] and represent a wide range of actual soils.
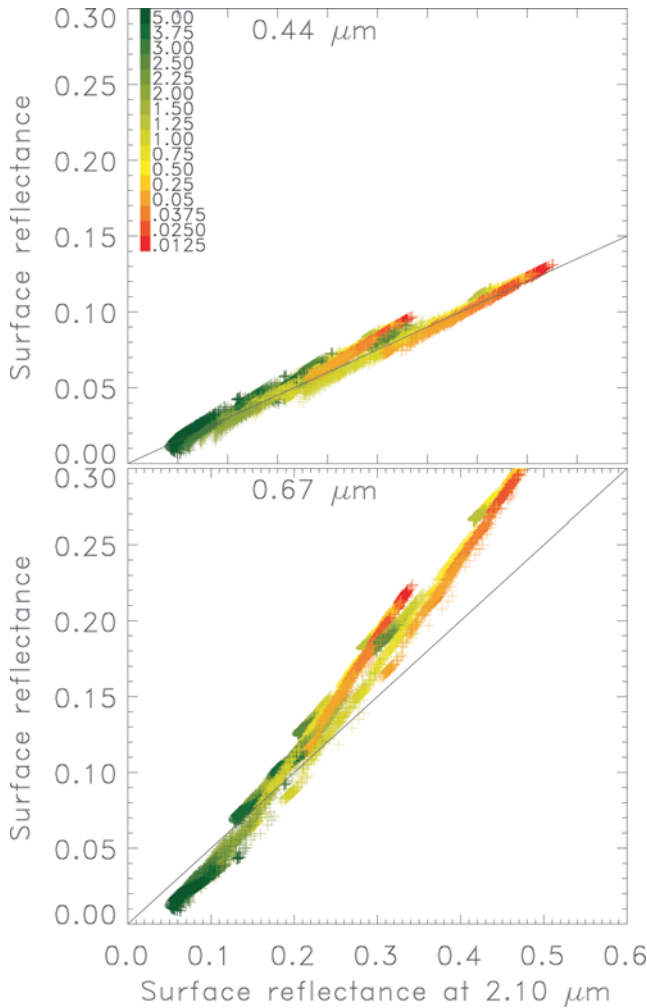
Figure 2. Scatter plots of the simulated mixed surface reflectance at 0.44 μm (top) and 0.67 μm (bottom) as a function of the reflectance at 2.1 μm for medium and bright soils (see Table 1). The vegetation density is represented by the color bar, varying from dark green for $f_v*LAI = 5$ to red for $f_v*LAI = 0.01$. f_v is the vegetation fraction, and LAI is the leaf area index. Lines for the ratio of 1/4 and 1/2, assumed in the MODIS algorithm [*Kaufman et al.*, 1997a] are also shown. The calculations are performed for view zenith angles (0° to 40°), solar zenith angle (1° to 51°) and azimuths of 0°, 90° or 180°.

reflectance are shown in Figure 4 for two solar zenith angles: 21° and 51°, representing conditions of high and low Sun. They are represented as a function of the view zenith angle. The figures correspond to full and half fractional vegetation covers, for LAI varying from 0.05 to 5 and for conditions where the reflectance at 2.1 μm is less than 0.25.

[9] It can be seen that the ratios are weakly dependent on the view zenith angle for low solar zenith angle. They are also weakly dependent on view zenith angle for vegetation mixed with soil. The dependence is stronger for higher solar zenith angles over full vegetation cover. Under such conditions and for view angles ~40° MODIS will underestimate the aerosol optical thickness, by less than ~0.1. This error can be corrected by accounting, in the MODIS

algorithm, for the angular dependence suggested by the model.

4. Discussion and Conclusions

[10] A model describing the transfer of radiation through a vegetation canopy composed of randomly oriented leaves is used to formulate a theoretical basis for the empirical relationship between the surface reflectances in the blue, red and 2.1 μm channels assumed in the MODIS aerosol algorithm. The calculations were carried out for a wide range of leaf area index and vegetation fractions, using a linear mixing between vegetation and soil reflectances.

[11] We show that the reflectance in the blue is consistently 1/4 of the reflectance at 2.1 μm for all analyzed cases over medium and bright soils. This finding extends the limited empirical basis of the MODIS aerosol algorithm to many environments found around the globe.
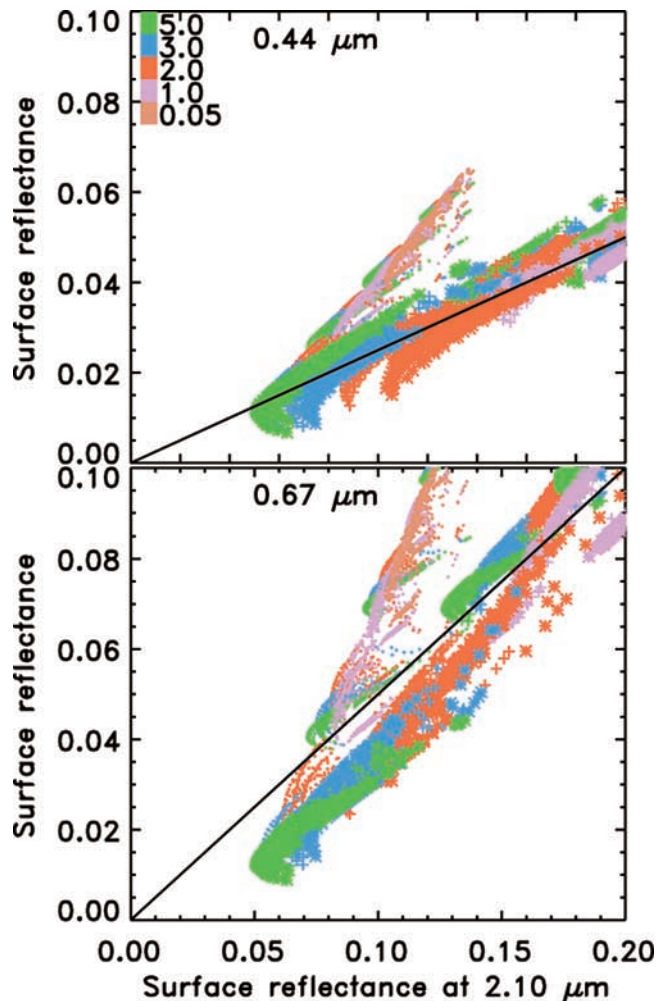

Figure 3. Similar calculations to those in Figure 2, but including the dark soil reflectance (dots) from Table 1. The scale of the surface reflectance is limited here to a lower range of 0 to 0.2. The colors represent the leaf area index, LAI not the vegetation density (f_v*LAI value as in Figure 2), which varies from 0.05 to 5. For each LAI value, the vegetation fraction varies from 0.25 to 1.0. The calculations are performed for view zenith angles (0° to 40°), solar zenith angle (1° to 51°) and azimuths of 0°, 90° or 180°.
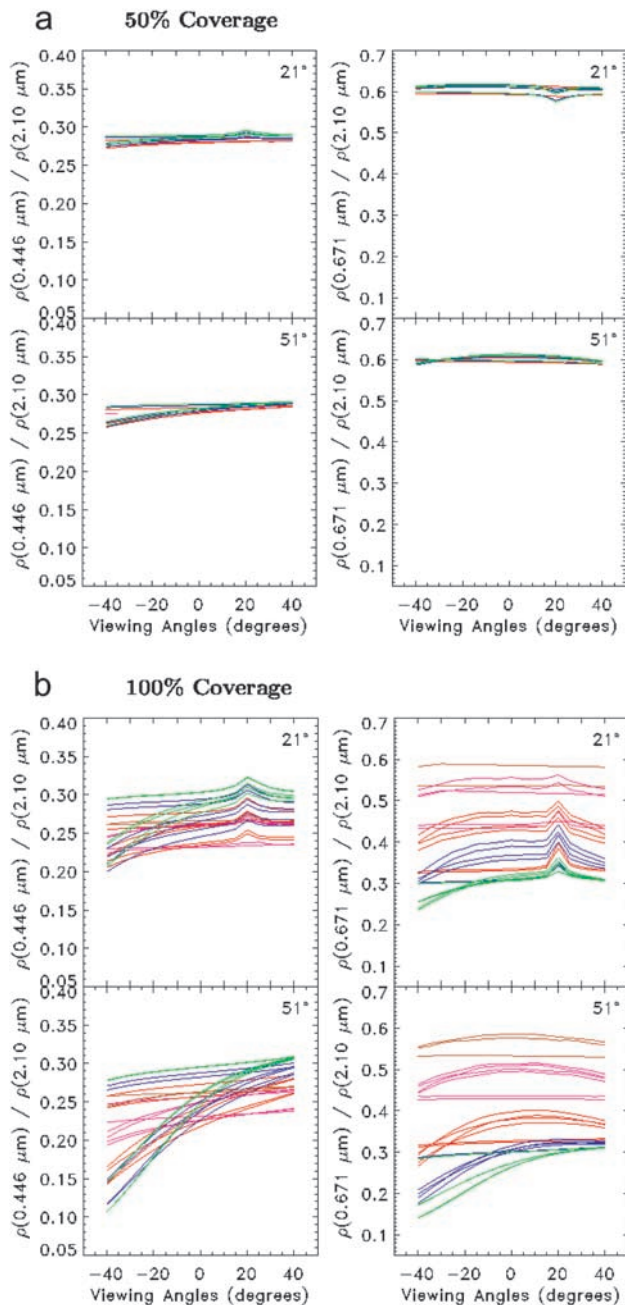
a   50% Coverage

b   100% Coverage

Figure 4. Ratios of the blue (0.44 μm) and red (0.67 μm) reflectances to the 2.1 μm reflectance, represented as a function of the view zenith angle for solar zenith angles of 21° and 51°, typical of high and low Sun. The figures are given for half (top) and full fractional vegetation cover (bottom), for conditions where the reflectance at 2.1 μm is less than 0.25. The LAI varies from 0.05 to 5 following the color convention used in Figure 3. The calculations are performed for view zenith angles (0° to 40°) and azimuths of 0°, 90° or 180°.

[12]   The ratio of the reflectance in the red to that at 2.1 μm varies from slightly less than the empirical value of 1/2 for dense and dark vegetation ($\rho_{2.1} < 0.1$), to slightly more than 1/2 for situations involving vegetation mixed with bright soils. This is in agreement with aircraft measurements over uniform dense vegetation [*Remer et al.*, 2001, *Gatebe et al.*,

2001] and over exposed soils but not for cases where vegetation is mixed with dark soils. One possible explanation for the differences for mixed scenes is the effect of shadows in an uneven terrain or uneven height of vegetation. Neither effect is explicitly included in the present model calculations. For example, a reflectance at 2.1 μm of $\rho_{2.1} = 0.1$ corresponds to a surface reflectance of $\rho_{red} = 0.035$ in Figure 2 or 3. However using values from Figure 2 we can construct a surface cover with a combination of 60% of dark surface ($\rho_{2.1} = 0.06$ and $\rho_{red} = 0.015$) with 40% of bright surface ($\rho_{2.1} = 0.30$ and $\rho_{red} = 0.18$). If this combination is 35% shadowed and if these shadows are totally black in both channels, the linearly composited reflectance gives the same reflectance at 2.1 ($\rho_{2.1} = 0.10$) but higher reflectance in the red of $\rho_{red} = 0.052$, than the original value of $\rho_{red} = 0.035$.

[13]   Nevertheless, and in agreement with the mentioned aircraft measurements, the conclusion of this study is that for very dark surfaces (e.g., $\rho_{2.1} \leq 0.06$) the surface reflectance in the red channel may be overestimated by assuming a ratio of 1/2, resulting in an underestimate in the derived aerosol optical thickness. A smaller ratio should be used, however more extensive field and modeling experiments have to be conducted in order to better quantify this ratio.

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